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MILES PRESSURE/SEISMIC RESPONSE-INITIAL STUDY AND ANALYSIS.(U)

JUN 77 J B STARR, M R LUDWIG, B E BARNES F30602-76-C-0385

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Final Technical Report
June 1977

MILES PRESSURE/SEISMIC RESPONSE
Initial Study and Analysis

Honeywell Inc.

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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This is an initial study and analysis of a method for testing the pressure/seismic response of a MILES transducer. The testing approach described is based on an experimentally verified mathematical model for the line transducer. A preliminary design for a test apparatus and a test procedure not only evaluates the pressure/seismic response, but also develops all additional data required for acceptance testing of a MILES transducer.

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EVALUATION

This effort lays the foundation for the development of a test fixture and procedures suitable for production testing of the MILES cable. To date, the MILES cables have been bought in limited quantity and acceptance testing has consisted of actual field evaluation of a sample number of lines. This method is entirely unsatisfactory for procurement in production volume. The test fixture configured from the initial study and analysis maximizes automation of the entire test sequence through data printout. This provides a practical technique for accomplishing the volume of testing required while minimizing the introduction of operator error. Based upon this initial study and analysis, an advanced development model of the device will be built and evaluated. Ultimately, a limited number will be built and supplied to the Base and Installation Security System Program Office for use by contractors supplying the MILES cable.

ROBERT B. CURTIS
Project Engineer

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SECTION I
SUMMARY

This report summarizes Phase I of a program to develop a pressure/seismic test apparatus and procedure for MILES transducers. The apparatus will provide a means for measuring and documenting sensitivity so that satisfactory performance can be ensured prior to carrying out installation in a security system. As a result, replacement of transducers necessitated by anomalous sensitivity characteristics can be kept to a minimum. Where anomalies occur, the apparatus may, in some situations, provide information for diagnosing the problem as being either transducer- or environment-related.

The mathematical model for pressure/seismic sensitivity presented is based primarily on data in the literature. The governing transduction mechanism is associated with the magnetostrictive properties of the core of the transducer. A signal is generated in sense windings when soil motion generates tension and/or compression loads within the core. The loads result in a change in magnetic flux that generates an e.m.f. in the sense windings.

The resulting formulation forms a basis of an acceptance criterion. In-plant test data can be related to performance in an actual security system. The data is readily expressed in terms of a range at which a specified intruder disturbance is detected.

An analysis verification is provided. It is based on experiments reported in the literature and experiments carried out as part of this study. Laboratory measurements of stress sentitivity of a line transducer are correlated with data acquired for a buried transducer. Variability of sensitivity is evaluated through both laboratory measurements and measured

response of a buried line. The data indicate that the standard deviation of sensitivity ranges from 15 to 20 percent of mean sensitivity.

A preliminary apparatus design—based on the verified mathematical model—is described. The design provides for testing not only pressure/seismic response, but also magnetic sensitivity, sense winding resistance, insulation resistance, line length, distance between winding reversals, and number of sense winding reversals. The apparatus will thus furnish all data required for acceptance testing of the MILES transducer.

SECTION II
INTRODUCTION

The MILES transducer provides an effective means for intrusion detection in perimeter security systems. The transducer is essentially a cable, 100 meters in length, that is usually buried at a depth of 9 inches, but may be buried at least as deep as 18 inches. The core of the cable is a permalloy material possessing high permeability and magnetostrictive properties. A sense winding is wrapped about the core. The winding direction is reversed periodically to provide a gradiometer configuration that results in rejection of far-field disturbances. By virtue of the high permeability of the core, the transducer is sensitive to anomalies produced within the earth's magnetic field, as, for example, by an armed intruder. By virtue of the magnetostrictive properties of the core material, the transducer is sensitive to small soil displacements, which may be caused by an intruder. The transducer has been widely deployed in a "round" configuration in which the core is a stranded bundle of permalloy material and an outer layer of thermoplastic material provides protective covering. In recent years a "flat" configuration has been developed in which the core is flat permalloy strip and a seam-welded stainless steel jacket forms the protective cover.

Although both of these transducers have been used successfully in security systems, variations in sensitivity have been observed. The cause of these variations may be due to either the burial environment encountered or may be inherent in the transducer. Currently, there is no information or technique available for assessing pressure/seismic sensitivity. Consequently, when anomalous performance is observed, little guidance can be provided for remedial action.

This report summarizes the results of the initial phase of a program that will provide an apparatus and test procedure for in-factory measurement of pressure/seismic sensitivity of MILES transducers. The scope of this phase encompasses a transducer analysis that provides a mathematical model of the transducer, a validation of the analysis based on data in the literature and controlled experiments, and the preliminary design of a test apparatus and procedure.

The results reported here are intended to provide a firm basis for a program to generate an advanced development model of a test apparatus.

SECTION III
THEORETICAL BASIS FOR TESTING

The design of an apparatus for pressure-seismic testing of a MILES line transducer should be based on a thorough understanding of its response mechanisms. In general, it is not possible to fully simulate in a factory environment the load and media conditions of an actual security system installation. Design of a meaningful test method must therefore be aimed at quantifying design parameters critical to transducer response in an actual installation. Such an approach requires an analytical model that realistically represents transducer response.

Analytical Approach

In analytically representing the MILES transducer, significant simplications follow from two factors:

(1) The transducer, by virtue of periodic sense winding reversals, will tend to reject signals of a spatial scale much larger than the distance between reversals.

(2) The currently used signal processing electronics, with its limited bandwidth, will result in response to seismic signals with wavelengths of about 10 meters or greater.

By way of example, consider a transducer which, with electronic filtering, limits response to frequencies below 10 hertz. Seismic waves propagate through top soil at velocities of about 100 meters per second and greater. The MILES transducer by virtue of the winding reversals acts as a gradiometer with a baseline of approximately one meter so that signals of 10 meters or greater wavelength are for the most part rejected. The gradiometer action eliminates seismic signals of 10 hertz and below; the electronics eliminates all signals of 10 hertz and above. Therefore, all seisimically propagated signals are rejected. In such a case, the inertial terms in the equations for soil displacement can be dropped and the solution for soil displacement is based on static loading. Although the actual loads of interest may be varying (e.g. at frequencies of 10 hertz and below), soil displacements at a given point in time can be calculated by assuming the load at that time is a static load. In other words, all soil motion of 10 hertz and below within a few meters of the transducer is in phase.

One may conclude from these arguments that meaningful testing of the MILES transducer does not encompass any seismic propagation phenomena. Thus, the testing may be more accurately termed as "mechanical" rather than "pressure/seismic."

Mathematical Model

Information in references (1) and (2) indicates that the MILES transducer responds primarily to longitudinal forces. These forces produce a change in magnetic flux within the core material because of its magnetostrictive properties. The relationship between flux change and force change is

$$\Delta\phi = \Lambda \Delta F_L{}^{*} \tag{1}$$

Bending of the line caused by vertical soil motion produces a negligible response.

Longitudinal forces are produced by the displacement of soil in the direction of the line. The force produced per unit length of line is proportional to the difference between soil displacement and line stretch, i.e.,

$$\begin{aligned} \frac{dF_L}{dX} &= G_S C_S (u_S - u_L) \\ &= G_S C_S \Delta u \end{aligned} \tag{2}$$

* Identification of mathematical symbols used in this report is found on page 37.

The equation governing Δu is

$$\frac{d^2(\Delta u)}{dx^2} - \frac{\Delta u}{\eta_{STR}} = \frac{d^2 u_S}{dx^2} \tag{3}$$

where

$$\eta_{STR} = A_L E_L / C_S G_S \tag{4}$$

The signal, in microvolts, produced by applying a sinusoidal vertical load equidistant from the ends of a line of length 2L is given by

$$\varepsilon = 200 \int_o^L n \Lambda \omega \frac{E_c A_c}{E_L A_L} \int_x^L C_s G_s \Delta u \, dx \, dx \tag{5}$$

For a given value of η_{STR} the parameter $G_s \Delta u$ will be proportional to the amplitude of the load (W) imparted to the soil surface. This suggests that equation (5) can be written in a more general form, thus:

$$\varepsilon = 2 \int_o^L \int_x^L \frac{\alpha G_s \Delta u}{W} \, dx \, dx \tag{6}$$

where

$$\varepsilon = \frac{100\, e}{\omega W n \Lambda \eta_c C_S} \tag{7}$$

$$\eta_c = \frac{E_c A_c}{E_L A_L} \tag{8}$$

The parameter η_c is in effect the ratio of the longitudinal rigidity of the core to the longitudinal rigidity of the complete line. Winding reversals at transpositions are taken into account by assigning either +1 or -1 to α. In equation (7), the constant 100 is added so that if lengths and displacements are in inches, forces in pounds, ω in radians per second, n in turns per inch, and Λ in maxwells per pound, e will be in microvolts. The unit of ε is inches.

Equations (3) and (5) provide a generalized expression for line transducer response. For a given surface load on a specified area, burial depth and range, the parameter ϵ is a function only of η_{STR}. The relationship between these parameters for a burial depth of 18 inches is shown in Figure 1.

Interpretation of Test Results

A basis for mechanical testing follows from the definitions of ϵ [equation (7)] and η_{STR} [equation (4)], and their interrelationship, as shown in Figure 1. Suppose one designates as a sensitivity acceptance criteria the range at which a prescribed disturbance is detected. With such a criteria it is also necessary to assume a certain soil condition so that a soil shear modulus is available for evaluation of η_{STR}. If, in addition, ϵ could be determined for a given load, one of the curves in Figure 1 could be used to evaluate a range at which detection would occur.

Assume that in a security system installation we want to determine at what range a vertical surface load W_i acting at frequencey ω_i produces a system output signal e_i (in microvolts) after the transducer output is amplified by a gain ratio g_i. The corresponding value of ϵ would be:

$$\epsilon_i = \frac{100\, e_i}{g_i \omega_i W_i \Lambda \eta_c C_s n} \tag{9}$$

In this expression, n and η_c [see equation (8)] are functions of transducer design. An experimental analysis in Section IV will suggest that C_s is approximately 0.1. There remains only the parameter Λ that has to be determined by mechanical testing of the transducer.

The parameter Λ may be evaluated through the use of an apparatus designed to produce controlled tension loads on a MILES transducer. An approach for configuring such an apparatus is illustrated by Figure 2. Clamps are applied at transpositions in such a way as to generate a preload tension of a few pounds within the transducer. The distance between clamps

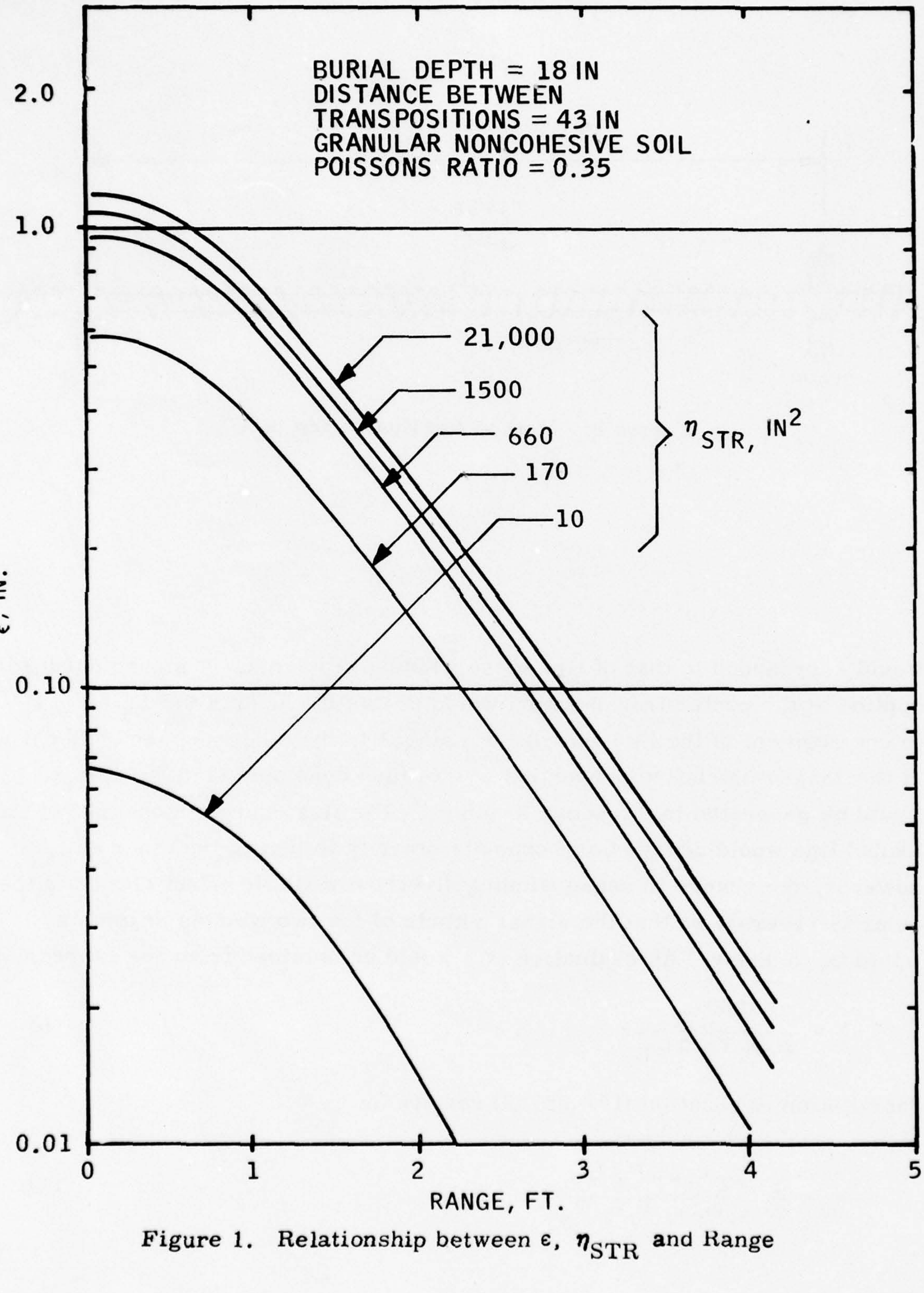

Figure 1. Relationship between ε, η_{STR} and Range

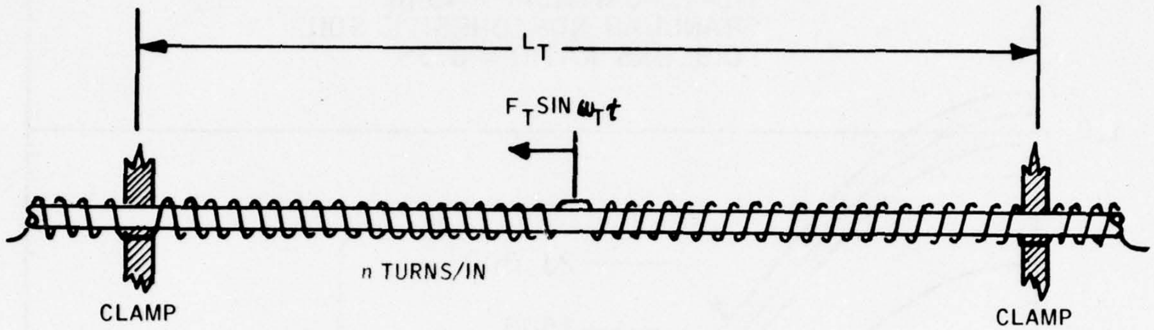

Figure 2. Method for Evaluation of Λ

would correspond to that of two sense winding segments. A sinusoidal load applied at the center transposition would create the load of $0.5\, F_T \sin\omega_T t$ in one segment of the line and $-0.5\, F_T \sin\omega_T t$ in the other segment. Because of the magnetostrictive properties of the lines core material, an e.m.f. would be generated in the sense windings. The flux charge in one half of the loaded line would always be of opposite polarity to that of the other half; however, the change in sense winding direction would in effect eliminate the polarity reversal so that the signal outputs of the two winding segments would be in phase. An evaluation of Λ would be obtained from the expression

$$\Lambda = \frac{200\, e_T}{g_T \omega_T F_T\, n\, L_T} \tag{10}$$

Substitution of equation (10) into (9) results in:

$$\epsilon_i = \frac{1}{2}\, \frac{g_T\, e_i\, \omega_T\, F_T\, L_T}{g_i\, e_T\, \omega_i\, W_i\, \eta_c\, C_s} \tag{11}$$

Equation (11) provides a means for evaluating range of detection of a given load based on data acquired from a testing machine. Assume that as an evaluation criteria the intruder produces a vertical load of 150 pounds peak-to-peak at a frequence of 2π radians per second. A threshold signal e_i of 2×10^6 microvolts peak-to-peak through a gain of 1.6×10^6 is desired, and C_s is assumed to be 0.1. The length of the test section L_T is equivalent to the length of two sensing winding segments. The test load F_T is set at one pound with a frequency of 2π radians per second. Substitution into equation (11) yields:

$$\epsilon_i = \frac{3.58 g_T}{e_T \eta_c} \text{ in}^{-1} \tag{12}$$

For a transducer buried at a depth of 18 inches in sand, the soil shear modulus G_s would be approximately 4600 psi. With a C_s of 0.1,

$$\eta_{STR} = \frac{A_L E_L}{460} \text{ in}^2 \tag{13}$$

For a given line design, one knows the values of A_L, E_L and η_c. From the test apparatus one measures e_T through a gain g_T. Thus η_{STR} can be calculated from equation (13) and ϵ_i from equation (12). By use of the correct curve in Figure 1, the range of detection can then be evaluated.

This analysis shows that test measurements can be directly related to performance of an installed line. For a given transducer design, only one measurement is needed. The test method should specify a tension loading (e.g., one pound at 2π radians per second) and a signal gain. The measured output signal can then be used as an acceptance criterion for mechanical sensitivity.

SECTION IV
VALIDATION OF THEORETICAL BASIS

The theoretical basis presented in the preceding section requires validation if the test approach is to be used with confidence. Sources of validation are data in the literature augmented by experiments that may be needed to resolve residual issues. Key issues that must be resolved either by prior experiments reported in the literature or experiments included as part of this study are:

(1) Is the MILES transducer mechanical response due primarily to magnetostrictive phenomena?

(2) Does the transducer respond primarily to longitudinal loads?

(3) Is the rationale valid that suggests that a MILES transducer does not respond to seismic signals at frequencies under 10 hertz?

(4) What value should be assigned to C_s?

(5) What variability in mechanical sensitivity may be expected?

The first three issues have been addressed in the literature and are briefly discussed in paragraphs that follow. The last two issues call for experiments that have been conducted as part of this study, and will be discussed in later paragraphs.

The first two issues are addressed in reference (3) through a combination of experiments and analysis. Laboratory experiments demonstrated that if magnetostriction were involved in transducer response, its manifestation would be only through loading the line in pure tension or compression. Bending produces no net magnetostrictive response. This is because the flux change produced by a stress has a polarity that is always the same as that of the stress. In bending, as much tension as compression load is produced within the core of the transducer. Hence, the flux change within the core would of necessity be zero. Any net flux change due to bending would be caused by rotation of the core material within the earth's magnetic flux.

The extent to which bending and longitudinal loading govern mechanical response was demonstrated by a simple field experiment reported in reference (3). Bending of the buried transducer would result from vertical soil motion caused by a vertical load at the soil surface. Longitudinal loading would have to result from accumulative shear loadings caused by horizontal soil motion in the direction of the line. Careful consideration of what flux changes would occur with these two loadings, and the fact that sense windings are reversed every 43 inches, lead to the following conclusions:

- Any transducer response to a vertical load at the soil surface midway between winding reversals is due only to magnetostriction caused by tension loading.
- Any transducer response to a vertical load at the soil surface directly above winding reversals is due only to bending.

These conclusions suggested an obvious experiment: have a subject cross the transducer at a winding reversal and at a midpoint and observe the magnitude of the response. When this was done, as reported in reference (3), a much larger response was observed with the midpoint crossing. Careful measurements reported in reference (1) showed a similar result to the extent that sensitivity at reversals was found insignificant relative to sensitivity at midpoints. These results validate the postulates of issues (1) and (2) that response is due primarily to magnetostriction and that the response is a result of longitudinal loading of the transducer.

The third issue deals with the method with which soil motion is represented. As discussed in Section III of this report, if seismic waves can be ignored, then inertial terms can be disregarded in the equations for soil motion, and the problem is greatly simplified. Under such a condition, transducer response would be proportional to the magnitude of the load at the soil surface. Also, because the transducer signal is proportional to the rate of change of magnetic flux within the core, the signal amplitude would be proportional to load frequency. Thus, at a given load point near the transducer, the value of transducer output divided by load magnitude and frequency would not vary with magnitude and frequency. Experiments reported in reference (1) revealed that at frequencies up to 20 hertz such invariance did exist. Based on those data, the rationale that suggests the transducer does not respond to seismic waves at frequencies under 10 hertz is validated.

The remaining two critical issues relating to the value of C_s and variability in transducer performance have been dealt with through both laboratory and field experiments which are discussed in the following paragraphs.

Variability Studies

Variability in line transducer performance has been experimentally evaluated through both laboratory and field experiments. Laboratory experiments made use of the apparatus shown schematically in Figure 3. This apparatus is designed to produce a one-hertz tension load on a two-foot-long sample of core material in a controlled vertical colinear magnetic field.

The procedure followed in acquiring stress sensitivity data is to first adjust the apparatus to produce a 0.63-pound, peak-to-peak load at a one-hertz frequency. The field coil is energized and the current level varied to oscillate the vertical field magnitude several times from -3.5 to +3.5 Oersteds. This forces the magnetic state to a given hysteresis loop.

The output signal from the sense coil is measured with a high-gain, high-input-impedance amplifier driving a chart recorder. Output signals are essentially sine waves. Polarity of the output signal is established by referencing to a mechanically produced switch closure on the tension drive mechanism. Signals are recorded at several values of field intensity.

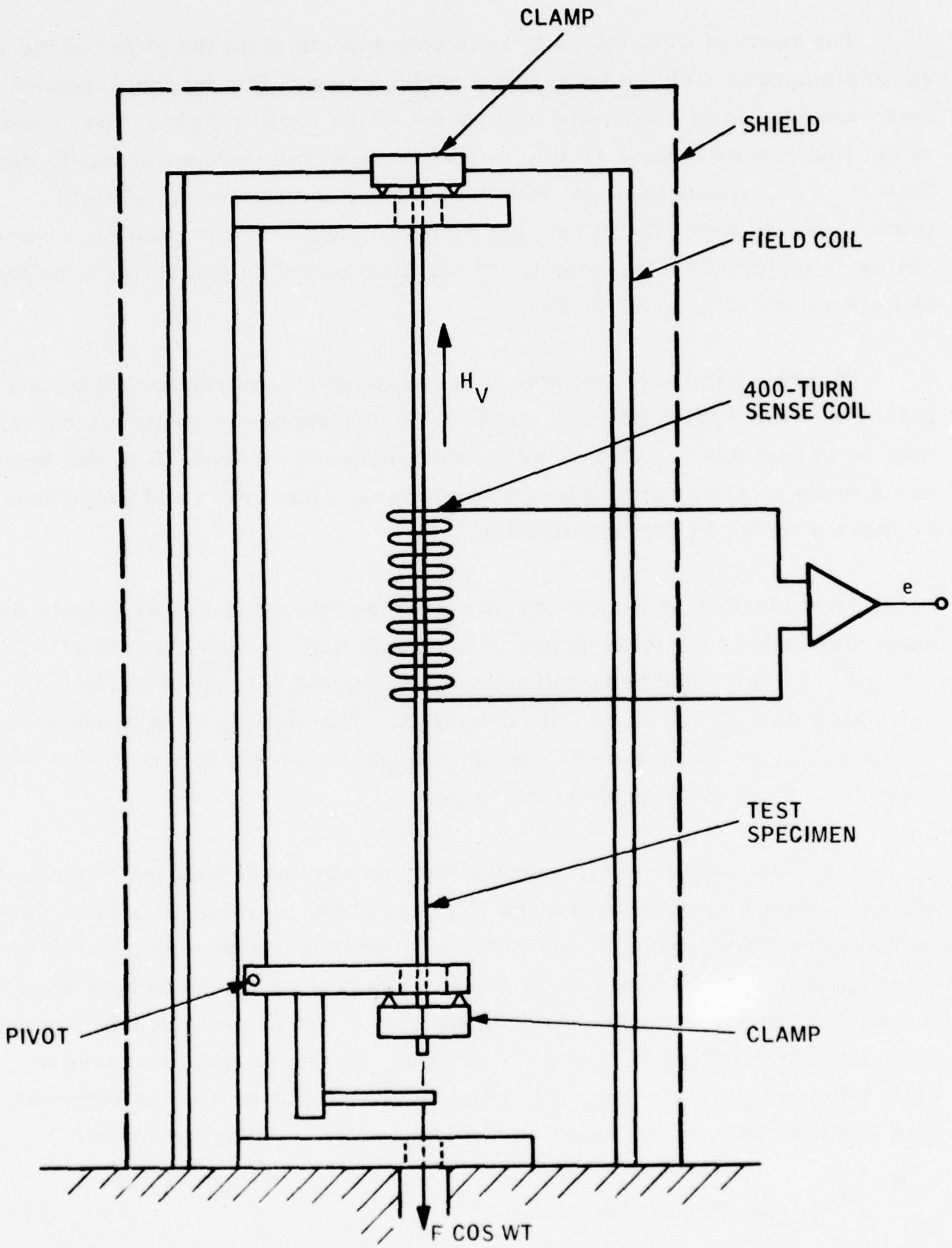

Figure 3. Apparatus for Measurement of Stress Sensitivity of Core Samples

The value of field intensity is intended to simulate the effect of the earth's magnetic field on transducer performance. For magnetic north-south orientation of a line, the component of the earth's field in the direction of the line ranges from 0.15 to 0.25 Oersteds within the continental United States. For a magnetic east-west orientation, the component of field intensity in the direction of the line would be zero. The evaluation of variability in material stress sensitivity was thus based on evaluating sensitivity at field values of zero and 0.25.

Figures 4 and 5 are typical of response data acquired for numerous samples of flat and round core stock. The differences in shapes of curves may be in part due to differences in demagnetization effect. The flat sample has a much smaller ratio of length to cross-sectional area and would thus be more affected by demagnetization.

An evaluation of variability was made by tabulating signal outputs for numerous samples at field values of zero and 0.25 Oersteds as shown in Table 1. Samples had been gathered over a period of several years from purchased lots of round and flat core stock. The statistical data presented at the bottom of the tables reveals one-sigma variations in sensitivity ranging from 25 to 35 percent of the mean values.

The relatively large variability indicated by these data led to an evaluation of variability of actual buried line transducers. Five 10-meter-long transducers were buried in sand. Surface loads of 100 pounds peak-to-peak were applied at a frequency of 10 hertz. Loads were produced by a special mechanical device described in reference (1) in which vertical loads result from counter-rotation of eccentric weights. Response was measured at eight points along each line, each point midway between winding reversals. The resulting data is presented in Table 2 in terms of the parameter

$$e^{*} = \frac{e}{\omega W} \quad (\mu\text{V sec/lb}) \qquad (14)$$

This parameter is used because it is essentially independent of load magnitude and frequency at frequencies under 20 hertz.

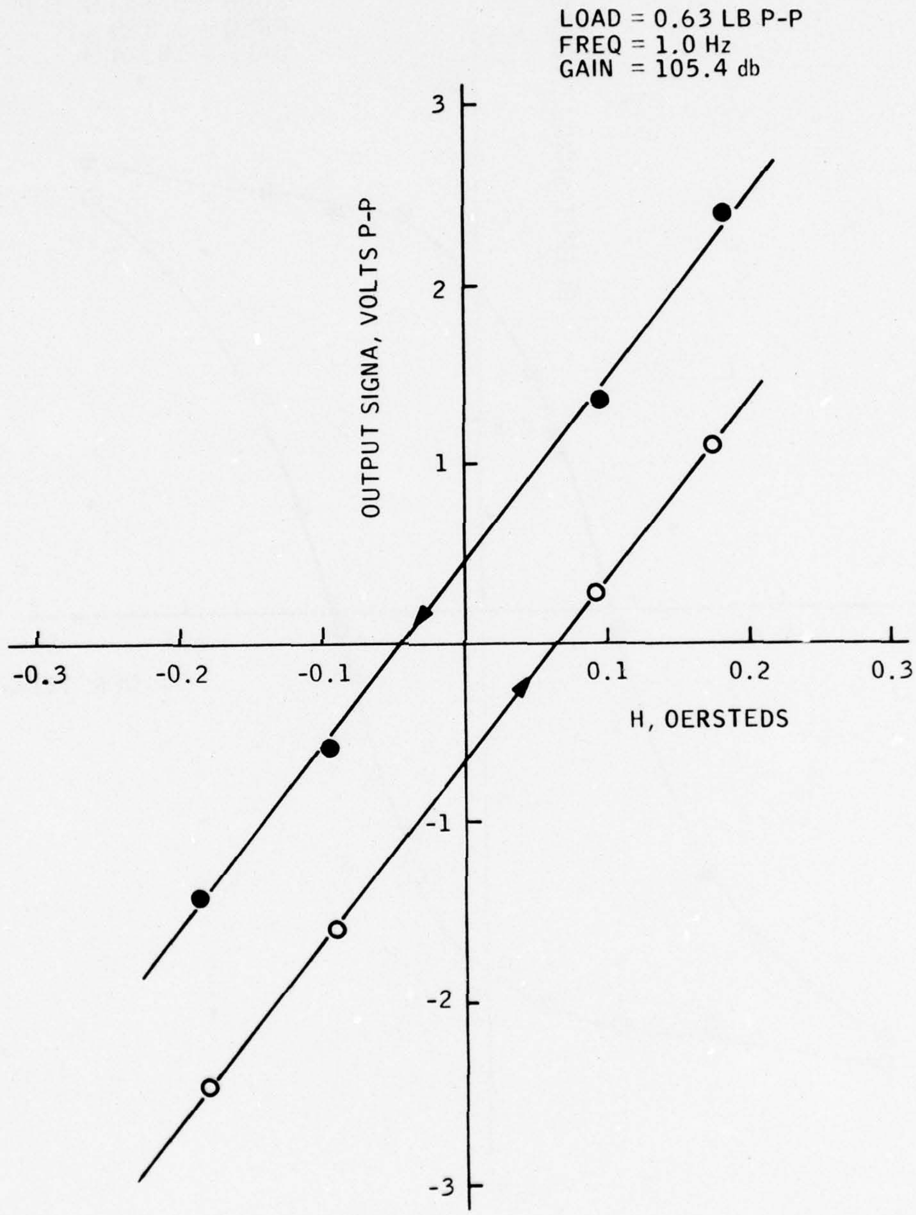

Figure 4. Response Data for 0.02- by 0.5-Inch Flat Core Stock

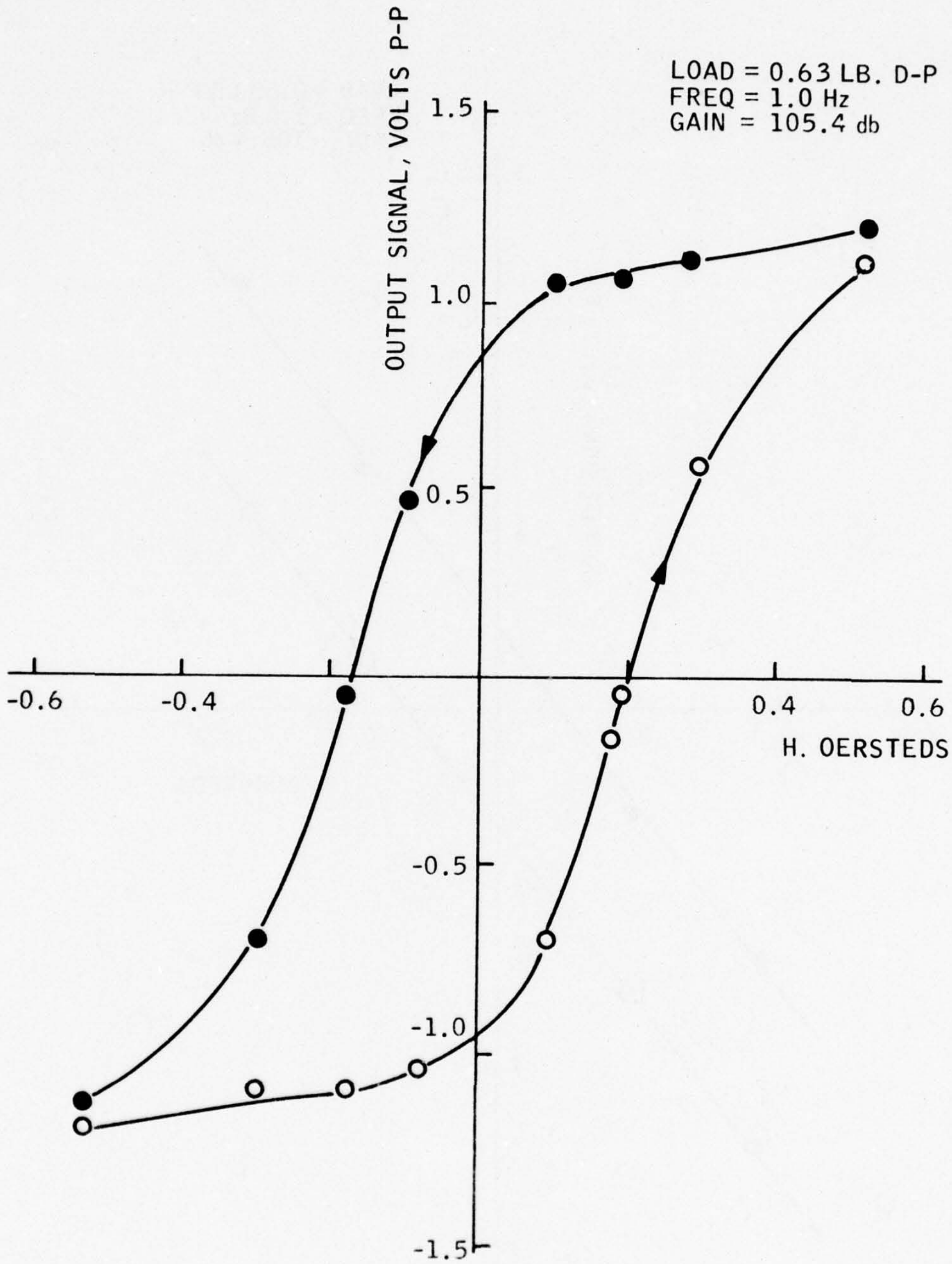

Figure 5. Response Data for 0.042-Inch Diameter Core Stock

Table 1. Output Signals (P-P) Produced by One-hertz Tension Load, 0.63-Pound P-P, Gain = 105.4 db

SAMPLE NO.	Output Signal, Volts	
	H = O	H = 0.25
1	0.59	5.14
2	0.79	3.89
3	0.72	3.87
4	0.62	3.00
5	0.71	3.81
6	0.58	3.28
7	0.49	3.22
8	0.35	2.48
9	0.61	3.76
10	0.45	3.15
11	0.34	0.82
12	0.98	3.83
13	0.79	3.99
14	0.77	3.62
15	0.44	3.14
16	0.36	3.41
17	1.11	4.61
18	1.04	4.62
19	0.66	4.16
$\bar{e}$	0.65	3.57
σ	0.23	0.87
$\sigma / \bar{e}$	0.35	0.25

(a) Flat Core Samples

SAMPLE NO.	Output Signal, Volts	
	H = O	H = 0.25
1	1.15	0.97
2	1.15	0.95
3	1.42	1.21
4	0.73	0.70
5	1.77	1.34
6	1.79	0.72
7	1.26	1.21
8	1.49	0.49
9	1.91	0.87
10	1.73	0.70
11	1.15	1.05
12	1.12	1.11
13	0.95	0.95
14	0.56	0.59
15	4.95	4.45
16	1.55	1.60
17	0.90	1.10
18	0.61	0.73
19	1.68	1.74
20	0.87	0.91
21	1.42	1.70
$\bar{e}$	1.06	1.03
σ	0.37	0.35
$\sigma / \bar{e}$	0.35	0.34

(b) Round Core Samples

Table 2. Variation in Response of Buried Line Transducers

SEGMENT NO	e *, μV SEC / LB				
	8OT. Flat 9-in Depth	8OT. Flat 18-in. Depth	Round 9-in. Depth	Round 18-in. Depth	Round 18-in. Depth
1	0.041	0.028	0.0082	0.0055	0.0087
2	0.066	0.042	0.0057	0.0093	0.0072
3	0.060	0.046	0.0055	0.0090	0.0053
4	0.065	0.055	0.0085	0.0084	0.0051
5	0.059	0.060	0.0093	0.0089	0.0091
6	0.045	0.057	0.0066	0.0081	0.0079
7	0.041	0.063	0.0087	0.0053	0.0064
8	0.039	0.060	0.0091	0.0047	0.0068
$\bar{e}*$	0.052	0.051	0.0077	0.0074	0.0071
$\sigma / \bar{e}*$	0.21	0.25	0.19	0.24	0.16

The data in Table 2 revealed one sigma variabilities that range from 16 to 25 percent of the mean output. Thus, the variability encountered with buried lines is somewhat less than that found in laboratory experiments on two-foot-long samples. The lower variability of buried lines probably results from the fact that the core of the actual line is continuous. Variabilities are thus somewhat reduced by magnetic coupling from point to point along the line. If a line were constructed with short magnetically uncoupled segments of core material, variabilities similar to those encountered in the laboratory would result.

The mechanical testing of a transducer using the approach suggested in Section III would probably encounter variabilities similar to those measured for buried lines. In-plant testing will be performed on complete lines rather than short samples. Thus, the reduction in variability alledgedly resulting from point-to-point magnetic coupling would be anticipated. One should therefore expect one-sigma variabilities in mechanical sensitivity, as measured by the proposed apparatus, ranging from 15 to 25 percent of the mean.

Evaluation of C_s

The last of the key issues to be addressed is the evaluation of the coupling coefficient C_s. This parameter is not derivable from theory by practical means. The theory does at best suggest that this value should be near 1.0. Essentially, determining its value is a final "fit" of the theory to experimental results.

The procedure followed in determining C_s was to measure a value of Λ by laboratory means for a sample of round line transducer. The sample was taken from one end of a 10-meter line. Data taken from the buried line was then matched to laboratory data through assignment of a certain value of C_s. Figure 6 is a schematic of a test setup used to measure Λ for a sample of round MILES. Two samples were used to form a closed magnetic loop so that demagnetization effects could be minimized. The H field was produced by passing a d.c. current through the MILES sense windings. Flux

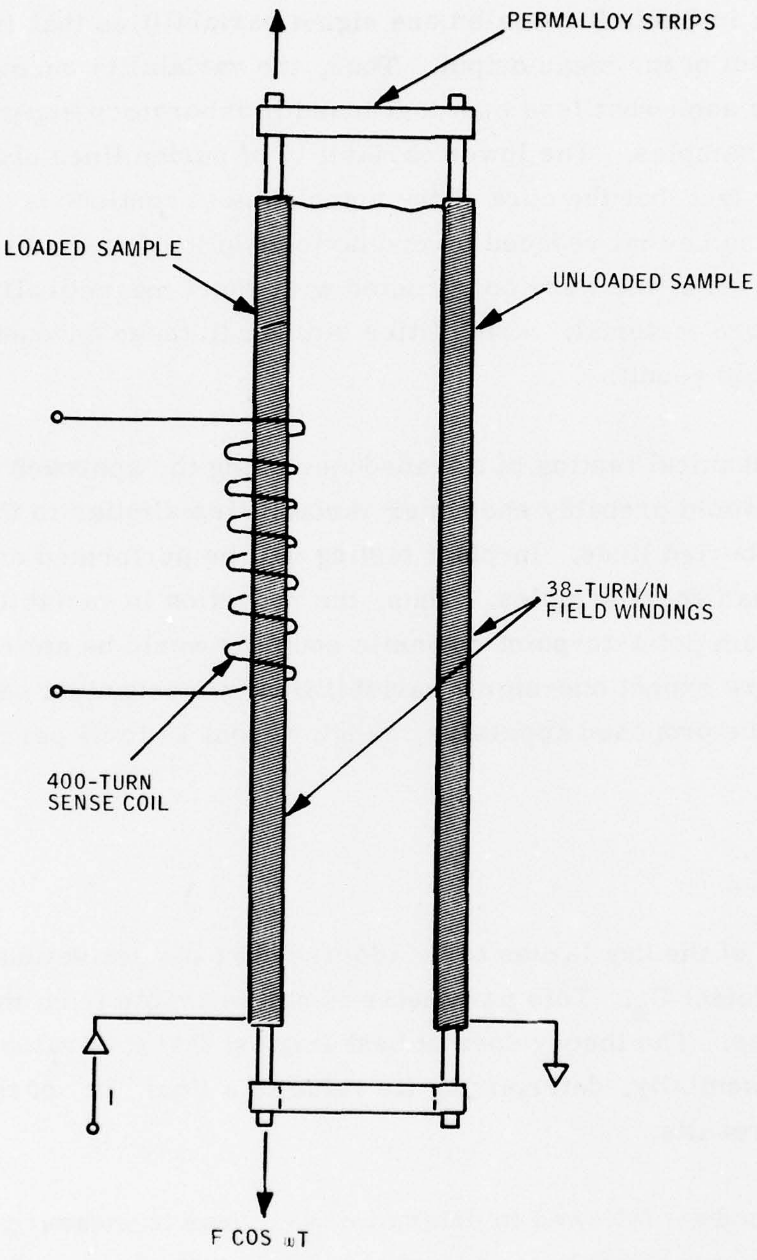

Figure 6. Schematic of Test Configuration for Measuring Stress Sensitivity of a Round Transducer Segment

changes within the core were measured using a 400-turn sense coil. The magnetic sensitivity in maxwells per pound was determined from the relation

$$\Lambda = \frac{e}{4\omega F} \tag{15}$$

where e is in microvolts, F is in pounds and ω is in radians per second. The data so obtained is shown in Figure 7. The average value of maximum sensitivity occurring at ±0.15 Oersteds is 0.17 maxwells per pound. A field value of 0.15 was selected to correspond to the earth-field component in the direction of the buried line.

The buried line from which the sample was taken is the one for which data is presented in the last column of Table 2. From that data we see that e* ranges from 0.0068 to 0.0087. From equations (7) and (14) we can re-write in the form

$$\epsilon = \frac{100e^*}{n\Lambda\, \eta_c C_s}$$

For the round line, n = 38 and η_c is approximately 1.0. Thus, using the laboratory measurement of Λ and the field data for e* we see that ϵ ranges from $0.105/C_s$ to $0.135/C_s$. The rigidity parameter is computed from equation (4) for

$$A_L = 0.026 \text{ in}^2$$

$$E_L = 30 \times 10^6 \text{ lb/in}^2$$

$$G_s = 4600 \text{ lb/in}^2$$

Thus $\eta_{STR} = 167/C_s$

Refer now to Figure 8 which contains a theoretical curve of ϵ versus η_{STR} for zero range. Also plotted on the graph are straight lines in which each

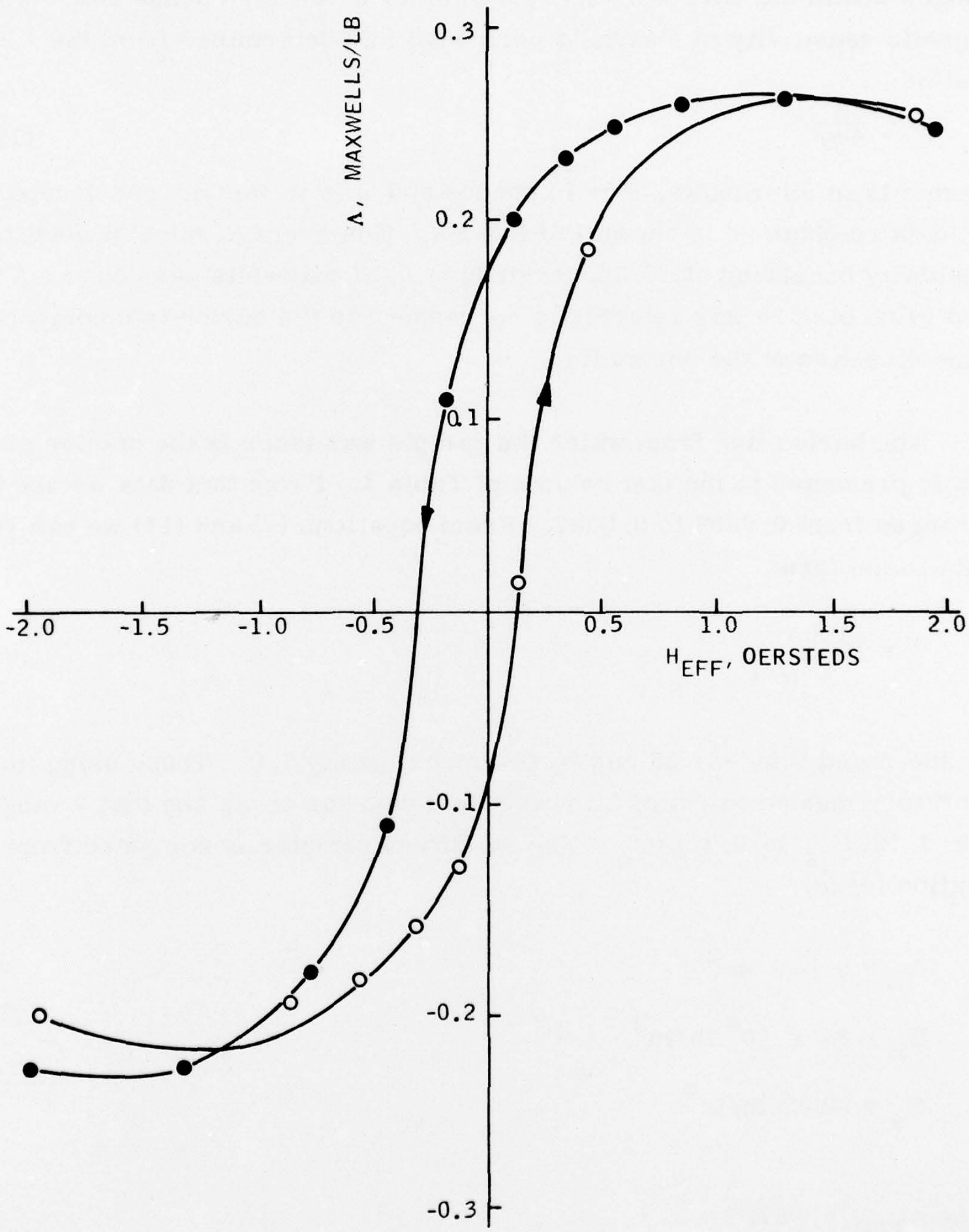

Figure 7. Stress Sensitivity of Round MILES Transducer Segment

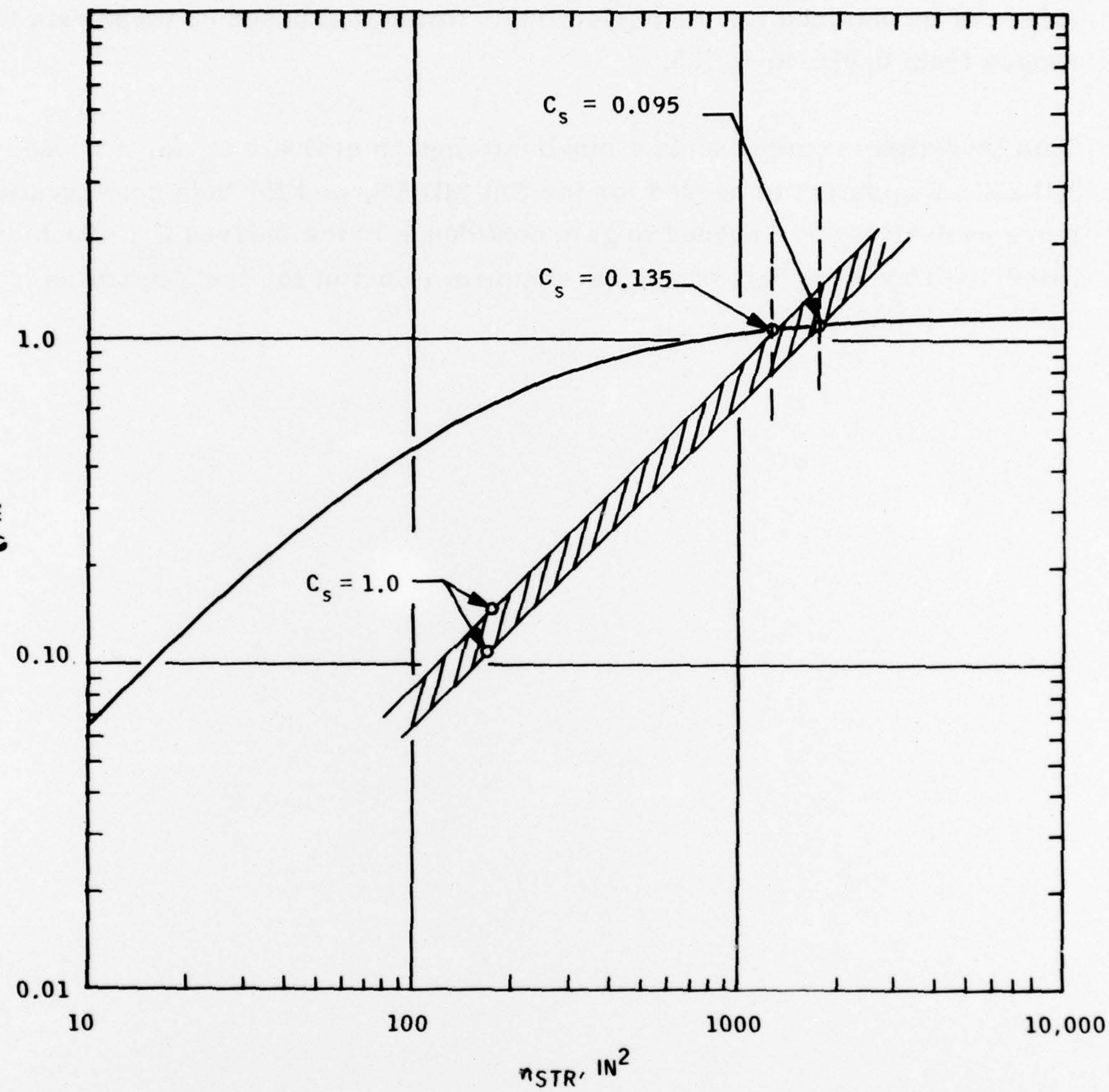

Figure 8. Graphical Determination of C_S

point would be a certain value of C_s. The two lines represent the extreme values of e* obtained for the buried line. Noted that based on these data C_s ranges from 0.095 to 0.135.

This investigation represents a single attempt to evaluate C_s for a round MILES. Evaluation is needed for the flat MILES, and for both configurations more evaluations are needed to gain confidence in the derived C_s. Such data gathering should be part of the development effort of the test apparatus.

SECTION V
TEST APPARATUS AND PROCEDURE

The theory and verification presented in Sections III and IV, respectively, form the basis of the design concept for a test apparatus presented in this section. The apparatus embodies the mechanical testing approach illustrated by Figure 2. In addition to mechanical testing, features are incorporated in the design that facilitate total acceptance testing of line transducers.

Design Criteria

The apparatus for measuring mechanical sensitivity must be capable of imparting controlled tension loads to a finite length of the transducer. This must be accomplished in such a way as to ensure that load effects are indeed isolated to the section being tested, and that vibration and electromagnetic stimuli associated with a typical factory environment do not influence sensitivity measurements.

In addition to the requirements for mechanical testing, it would be highly desirable to incorporate as much of acceptance testing as possible into a single test apparatus and procedure; therefore, it would be desirable to measure, in addition to mechanical sensitivity,

- magnetic sensitivity
- sense winding resistance
- insulation resistance
- line length
- transposition lengths
- number of transpositions

The design presented in the following section will illustrate an approach that meets these design criteria.

Design Concept

The test apparatus design concept is illustrated in Figure 9. The design is based on the loading principle illustrated in Figure 2. The design is set up so that the connector end of a completed transducer can be threaded through the test section onto a takeup reel. At the takeup reel, the connector is tied into instrumentation through slip rings on the reel shaft. Key components of the apparatus are as follows:

Nulling Coils -- These coils generate 10-hertz sinusoidal magnetic fields that are detected via the transducer sense winding. The detected signal will be a minimum when a transposition is centered between the coils.

Clamps -- Clamps provide for mechanical isolation, preloading and sinusoidal mechanical loading of the section of the line being tested. The stationary tension clamps are first activiated. A pneumatic cylinder then produces a tension preload of 10 pounds. The tension lock serves to maintain the preload without allowing movement of the tension clamp during testing. The stress clamp, located midway between the stationary and tension clamps, is the means by which a sinusoidal load is imparted to the transducer. Such loads are produced by a motor-driven spring linkage. Clamps would be adaptable to either round or flat transducer configurations.

Field Coils -- Field coils can be driven to values of magnetic field intensity large enough to saturate the lines core material. After saturation the field intensity is returned to a prescribed value for magnetic and mechanical sensitivity measurements. This provision ensures that the magnetic state of the transducer is on the boundary of the magnetic and mechanical hysteresis loops during testing. Magnetic sensitivity is determined by creating a small prescribed sinusoidal field within the coils and then measuring the line response signal.

Shields -- Shields are provided to minimize response to the magnetic environment produced within the factory and to isolate the test section from earth's magnetic field.

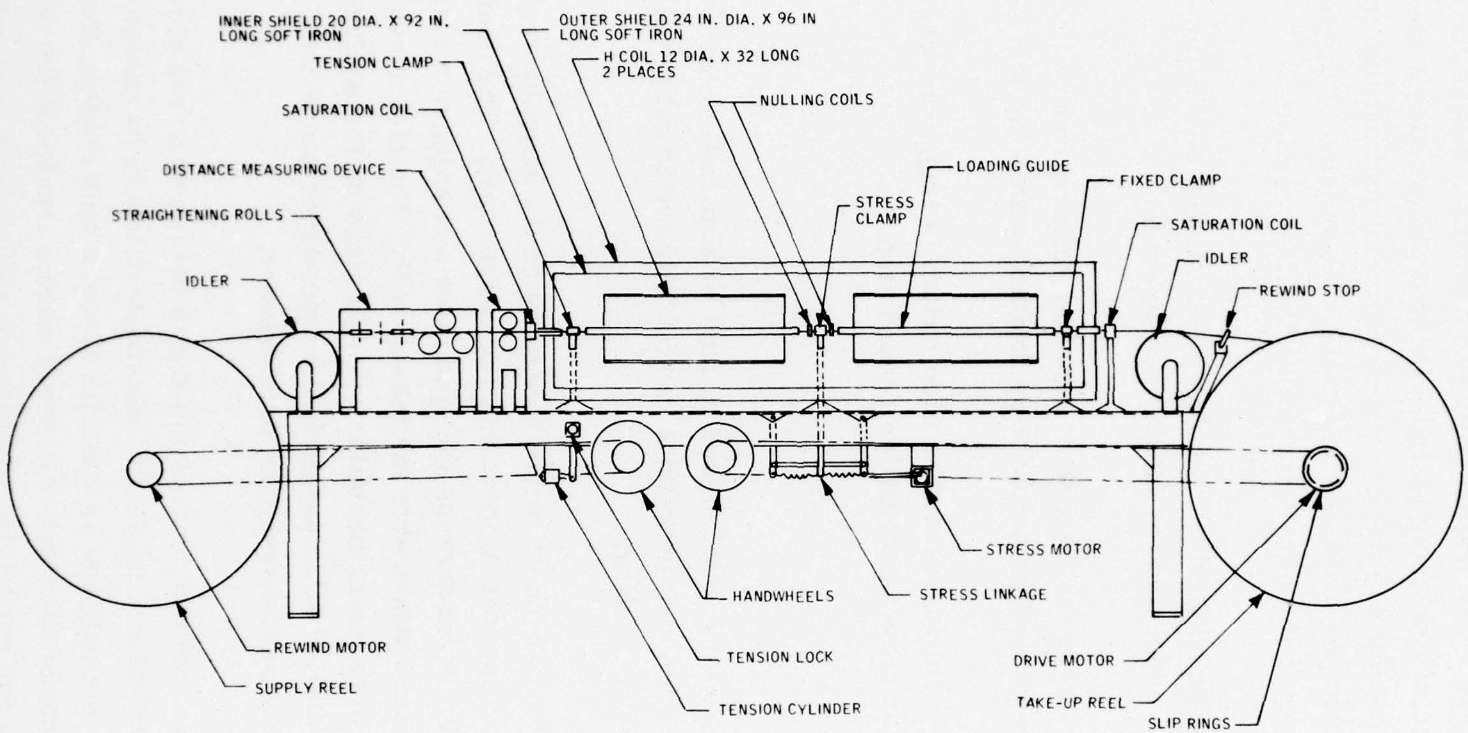

Figure 9. MILES Line Tester

Saturation Coils -- Saturation coils are a possible means for further isolating the section of line being tested. If the coils produce a steady field large enough to saturate the lines core material just outside the test section, then flux changes produced within the core outside of the test section cannot influence the core lying within the test section.

Distance Measuring Device -- A device consisting of a roller driving a counter is easily incorporated for length measurement.

Straightening Rolls -- Through a series of roller-produced bends, the line can be straightened prior to its positioning within the test section.

Rewind Stop -- During rewind, a stop switch is triggered when the transducer connector moves against the rewind stop.

Test Procedure

With suitable instrumentation and manual or automatic control of the test apparatus, the following procedure can be followed to gather all data required for acceptance testing.

The transducer is brought to the apparatus on its shipping reel, which, when installed on the apparatus, becomes the supply reel. The connector end of the transducer is fed through the apparatus and engages a male connector on a flex lead attached to the takeup reel. The electrical connection provides a tie-in to instrumentation via slip rings on the shaft of the takeup reel. Immediately after engaging the transducer connector, sense winding and insulation resistances can be measured.

The transducer can now be positioned at a series of points along its length where mechanical and magnetic sensitivities are to be measured. During positioning, the null coil is energized, and a null reading obtained via the transducer sense windings will occur when a transposition is located midway between the two null coils. A clamping sequence is then carried out whereby a 10-pound preload is imparted to the portion of the transducer lying within the test section. A drive motor is energized in order to impart a one-hertz mechanical load to the transducer via the stress clamp.

Prior to measuring mechanical or magnetic sensitivity, the field coils are energized to a level sufficient to saturate the transducer core material. Thereafter, the magnitude of the field is reduced to a level representative of the earth's field in the direction of the line, e.g., between zero and 0.25 Oersteds. Magnetic sensitivity is determined by measuring line response to a small sinusoidal field generated by the coils.

When all desired mechanical and magnetic sensitivity measurements have been made, the line is positioned with one end located at the distance measuring device. Clamps are released and the nulling coils are energized. The line is now rewound onto the supply reel. During rewind, transpositions are detected by noting signal polarity reversals occurring at the sense winding output. At each reversal a length measurement may be recorded. When rewind is complete, length measurements for each transposition, total line length, and the number of transpositions are known.

SECTION VI
CONCLUSIONS

The objective of this study was to develop a viable technique for in-factory measurement of the "pressure/seismic" (i.e., mechanical) response of either a flat or round MILES transducer. This objective has been attained. The design approach generated rests on the following conclusions:

1. Mechanical response of a MILES transducer is due to tension loads associated with soil displacement in the direction of the line; therefore, a viable approach for mechanical testing is to measure transducer response to tension loads in an environment that simulates operating conditions. The tension loading produces a change in magnetic flux within the core of the line, which in turn generates an e.m.f. in the sense winding wrapped about the core. Because the response is uniquely related to a magnetic phenomenon, it suffices to simulate the operating environment only in terms of a controlled magnetic field of magnitude similar to that of the earth's field.

2. Test data can be presented in terms of parameters that describe the transducer's ability to detect intruders. If an intrusion is characterized by a moving vertical load at the soil surface with a prescribed amplitude and frequency, then an estimate can be generated for the range at which the transducer signal would exceed a prescribed threshold.

3. A test apparatus can be developed that not only measures mechanical response, but also

- magnetic response
- sense winding resistance
- insulation resistance
- line length
- distance between winding reversals
- number of winding reversals

SECTION VII

RECOMMENDATIONS

This program has established a firm analytical and experimental base on which to carry out advanced development of an apparatus for in-factory testing of MILES transducers. The following recommendations are made with respect to the development of such an apparatus:

1. Recommendation is made that a program be initiated for generating an advanced development model of an in-factory test apparatus for the MILES transducer.

2. Within the context of the advanced development program, at least six flat MILES transducers, each 10 meters in length, should be tested as buried lines in a controlled soil sample (e.g., sand). Correlation between apparatus tests and buried tests should be carried out through evaluation of coupling coefficients.

3. Using the interim model of the apparatus, the effectiveness of various isolation techniques, clamping devices, magnetic field producers, mechanical load producers, and signal conditioning electronics should be thoroughly evaluated prior to freezing the configuration of the advanced design model.

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LIST OF SYMBOLS

A_C	Cross-sectional area of transducer core, in^2
A_L	Cross-sectional area of transducer, in^2
C_S	Soil-to-transducer coupling coefficient
e	Transducer output signal, μV
e^*	Transducer output parameter = $e/\omega W$, μV sec/lb
e_i	Amplified output of installed transducer, μV
e_T	Amplified output of transducer being tested, μV
$\bar{e}$	Average output at several positions along transducer, μV
E_C	Youngs modulus of core material, lb/in^2
E_L	Average Youngs modulus for transducer in tension, lb/in^2
F_L	Longitudinal force generated in transducer line, lb
F_T	Amplitude of tension load produced by the test apparatus, lb
g_i	Amplification of output of installed transducer
g_T	Amplification of output of transducer being tested
G_s	Shear modulus of soil, lb/in^2
H	Magnetic field intensity, oersteds
n	Sense winding turn density, in^{-1}
u_s	Soil displacement in direction of line, in
u_L	Line displacement due to tension or compression, in
Δu	Differential soil displacement $(u_s - u_L)$, in
W	Vertical load at soil surface, lb

x	Coordinate in direction of line, in
z	Axial coordinate in cylindrical system, in
α	Indicator of sense winding direction (= ± 1)
ϵ	Transducer output parameter, in
η_c	Ratio of longitudinal rigidity of core to that of the complete transducer [eq. (8)]
η_{STR}	Ratio of longitudinal rigidity of transducer to soil stiffness [eq. (4)], in^2
Λ	Core material stress sensitivity, maxwells/lb
ϕ	Magnetic flux, maxwells
ω	Signal frequency, radians/sec
σ	Standard deviation